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ANFO Calculations for Sedat Esen

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[Note to the reviewer: Sedat is an engineer in Australia who has provided the Reference Guide with much data. This is intended for a paper and more data for us comes because of it.]

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The calculations were run with JWL++, which is a simple reactive flow model run in a finite element code. The code is a 2-dimensional CALE-type arbitrary Lagrangian-Eulerian (ALE). This means that the problem geometry is broken into zones, each running according to Newtons' Law: force equals mass times acceleration. In the main Lagrange mode, each zone contains a fixed amount of mass. This can lead over time to tangling of zones, so a bit of Eulerian behavior is allowed in unimportant but less stable parts of the problem. This allows mass to flow between zones, thereby avoiding the tangling.

The problem is calculated in every zone and every time cycle, and the detonation progresses from the point of initation across the sample. The pressure is calculated from a linear combination of a Murnhan unreacted equation of state and a reacted explosive JWL. The rate of burn between these two species is set by a rate term with a detonation rate constant. We used the rate term

$$\frac{dF}{dt} = G_1 P^{b_1}(1-F)$$

where F is the burn fraction, G_1 the rate constant, and b_1 the power of the pressure (here set to 1). The JWL's and unreacted EOS coefficients are

Mb's	ANFO Prill	P700B Blend 1
ρ_o	0.80	1.15
A	1.5179110	2.844195
B	0.007146895	0.02754112

R_1	**5.0**	**4.8**
R_2	**1.0**	**1.2**
ω	**0.29**	**0.31**
E_o	**0.0350**	**0.0416**
$\Gamma_{cj}+1$	**3.9730740**	**4.035845**
D	**0.5050**	**0.5920**
C_o(cm/µs)	**0.023**	**0.067**
S_1 (dimlss)	**2.0**	**2.0**
n (dimlss)	**7.0**	**7.0**
κ ($Mbar^{-1}$)	**2463**	**194**

We first ran CHEETAH V3.0 for the detonation energies and ω. The values of R_1 and R_2 come from a general set based on the density. This was combined with the infinite-radius detonation velocity extrapolated from the data to make a thermodynamically balanced JWL. From previous runs, we knew that ANFO's have $b_1 = 1$. We were able to estimate the rate constant G_1 from the data but it is always a little different when run in the code. So we ran the smallest measured radius unconfined ratestick until we got the right detonation velocity. This occurred at a G_1 of 4 $(\mu s.Mb)^{-1}$ for the prill and 5 $(\mu s.Mb)^{-1}$ for Blend 1. Then we ran the other unconfined radii and hoped that the calculated curve matched the rest of the data. Finally, without seeing the confined data, we set up the problem with a rock liner and ran for the detonation velocity at the desired radii. No adjustment is made in going from the unconfined to the confined problem.

The code uses the U_s-u_p coefficients C_o and S_1 for calculating the rock properties. For the unreacted explosive, we estimate C_o and S_1 from the densities, but they are then turned into the Murnahan coefficients using

$$n = 4S_1 - 1$$
$$\kappa = \frac{1}{\rho_o C_o^2}.$$

The Murnahan EOS is

$$P_k(\text{unreacted}) = \frac{1}{n\kappa}\left(\frac{1}{v_k^n} - 1\right) = \rho_o U_s^2 (1 - v_k)$$

and the JWL EOS is

$$P = A\exp(-R_1 v) + B\exp(-R_2 v) + \frac{C}{v^{\omega+1}}.$$

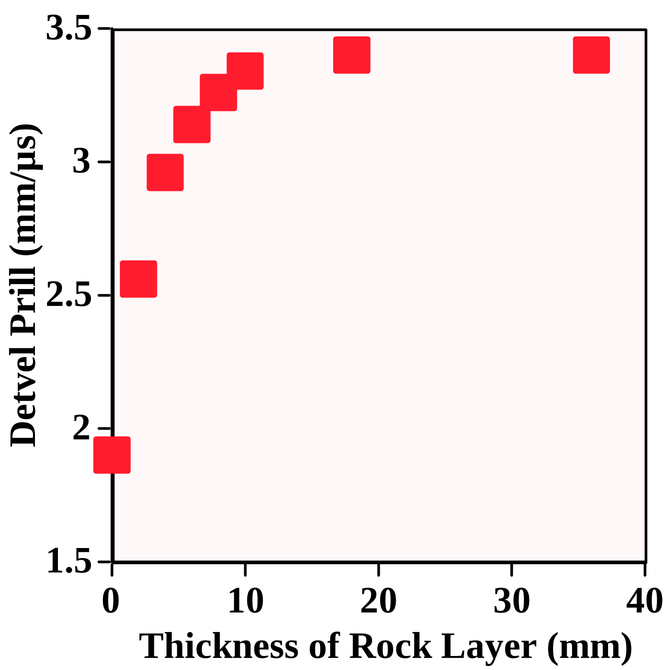
The unconfined measured data used for calibration is as follows.

Prill	diameter (mm)	radius (mm)	1/Ro (mm-1)	detvel (mm/µs)
	241	120.5	0.0083	4.13
	154	77.0	0.0130	3.82
	154	77.0	0.0130	3.85
	154	77.0	0.0130	3.58
	103	51.5	0.0194	2.57
	103	51.5	0.0194	2.70
	87	43.5	0.0230	2.50
	87	43.5	0.0230	2.51
	63	31.5	0.0317	2.13
		28 est		est fail

	diameter (mm)	radius (mm)	1/Ro (mm-1)	detvel (mm/µs)
Blend 1	236	118.0	0.0085	5.58
	236	118.0	0.0085	5.66
	236	118.0	0.0085	5.71
	150	75.0	0.0133	5.15
	150	75.0	0.0133	5.41
	150	75.0	0.0133	5.62
	130	65.0	0.0154	4.81
	130	65.0	0.0154	4.90
	130	65.0	0.0154	5.06
	101	50.5	0.0198	4.12
	82	41.0	0.0244	3.95
	82	41.0	0.0244	4.13

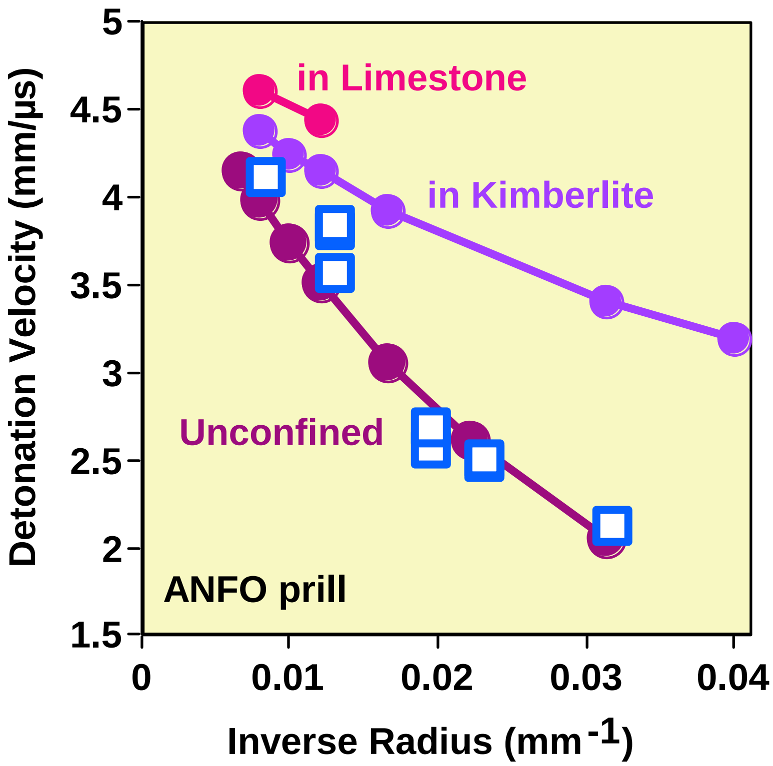
82	41.0	0.0244	4.34
82	41.0	0.0244	4.41
82	41.0	0.0244	4.67
69	34.5	0.0290	3.61
69	34.5	0.0290	3.69
69	34.5	0.0290	3.79
69	34.5	0.0290	3.82
69	34.5	0.0290	3.94
58	29.0	0.0345	3.78
	20 est		est. fail

One other issue needs to be described. The rock will be put into the code problem as a tube, but we need to know how thick the rock has to be. We therefore run the 30 mm radius ANFO prill ratestick with various thicknesses of kimberlite, and we get this picture.



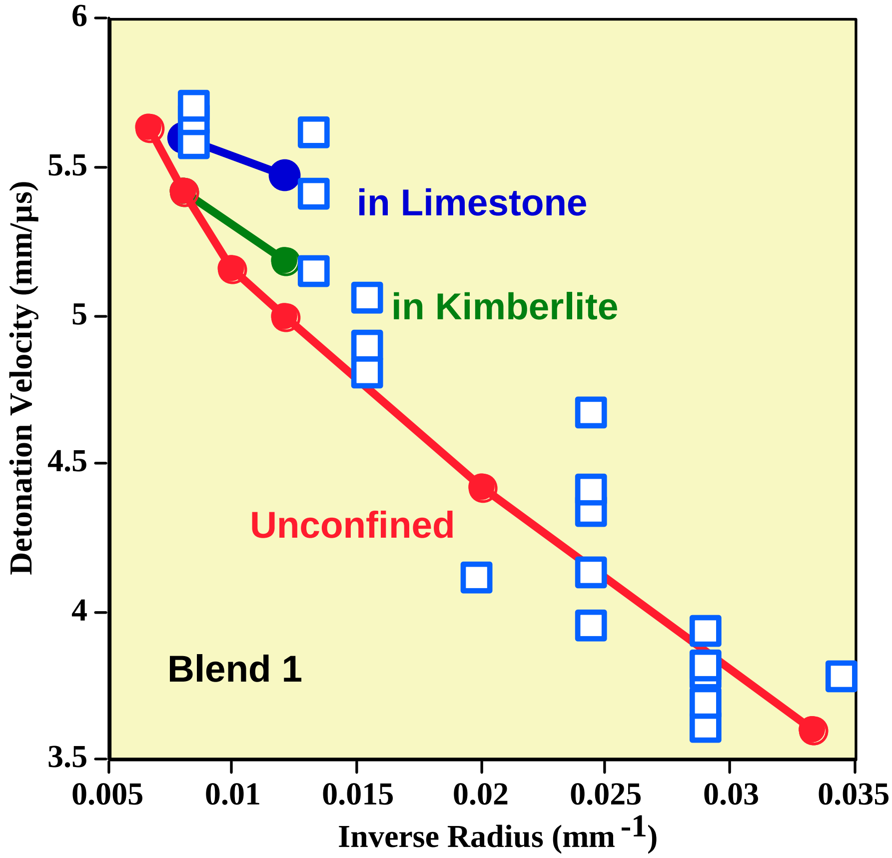
This says that 10-15 mm of rock is enough to get steady state detonation velocity in the problem, so we don't have to go any thicker. You may recall the paper we did, which says that we get equilibration with a small layer of confining material if the detonation velocity of the explosive is higher than the sound speed in the wall, which is the case here. Having a thin wall means fewer zones, which the problem is less likely to break down.

The ANFO results are shown here



The blue squares are the unconfined data. The maroon line is the code fit, where we recall that only the last ball at the lower right is actually fit and the rest are derived. Then we calculate the increased det velocity in the two kinds of rock without changing any parameters.

Now we go to Blend 1



where we have the same layout.

For the purposes of your possibly wanting to replot these results, I list the numbers.

ANFO Prill
D 4.87

Radius (mm)	Inverse (mm-1)	Un-confined	Kimber-lite	Lime-stone
150	0.00667	4.153		
125	0.00800	3.984	4.390	4.610
100	0.01000	3.740	4.254	
82.5	0.01212	3.511	4.150	4.450
60	0.01667	3.054	3.922	
45	0.02222	2.616		
32	0.03125	2.059	3.404	
25	0.04000		3.190	

Blend1
D 6.36

Radius (mm)	Inverse (mm-1)	Un-confined	Kimber-lite	Lime-stone
150	0.00667	5.635		
125	0.00800	5.423	5.420	5.600
100	0.01000	5.160		
82.5	0.01212	4.993	5.190	5.470
50	0.02000	4.419		
30	0.03333	3.604		

ANFO prill 30 mm unconfined with various Thicknesses of Kimberlite

Thickness (mm)	Detvel (mm/µs)
0	1.906
2	2.567
4	2.964
6	3.149
8	3.269
10	3.340
18	3.404
36	3.405

References

For JWL++

P. Clark Souers, Steve Anderson, Estella McGuire and Peter Vitello, "JWL++: A Simple Reactive Flow Code Package for Detonation," Propellants, Explosives, Pyrotechnics, 25, 54-58 (2000).

Effect of wall materials on det velocity of cylinders

P. Clark Souers, Peter Vitello, Sedat Esen and H. A. Bilgin, "The Effects of Containment on Detonation Velocity," Propellants, Explosives, Pyrotechnics 29, 19-26 (2004).